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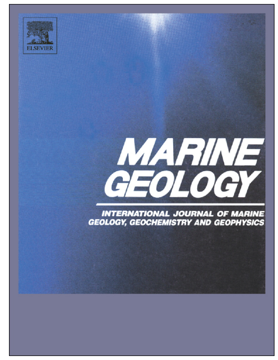

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GLACIAL AND SUBMARINE PROCESSES ON THE SHELF MARGIN OF THE DISKO BAY TROUGH MOUTH FAN

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Abstract

Fast-flowing ice streams and outlet glaciers exert a major control on glacial discharge from contemporary and past ice sheets. Improving our understanding of the extent and dynamic behaviour of palaeo-ice streams is crucial for predictions of how the chryosphere will respond to climate warming and the associated implications for global sea level. This paper presents results from two 3D-seismic surveys located on the continental shelf adjoining the Disko Bay Trough Mouth Fan (TMF), one of the largest glacial outlet systems in Greenland. Located at the seaward terminus of the c. 370 km long cross-shelf Disko Trough, the Disko Bay TMF was generated by highly efficient subglacial sediment delivery onto the continental slope during repeated ice stream advances. A variety of submarine glacial landform assemblages are recognised on the seabed reflecting past ice stream activity. The 3D-seismic study covers the shallow banks located north and south of the Disko Trough and sheds focus on the seabed and the uppermost stratigraphic interval associated with the late Pleistocene development. The buried section (probably of Saalian age) contains a prominent grounding-zone wedge (GZW) in the northern and low-angle progradational packages in the southern area, indicating a period of major glacial advances to the shelf margin. Subsequently, the outer margin was influenced by glacimarine sedimentation, localized shelf-edge ice advances and sediment transport by contour currents that possibly began in the last interglacial period (Eemian). During the last (de)glaciation, the northern bank appears to have been covered by passive ice leaving a field of dead-ice deposits. In contrast, multiple sets of terminal moraine ridges observed on the southern bank suggest a slow retreat of active, grounded ice from the Last Glacial Maximum position on the outer shelf. Isostatic and tectonic influences on relative sea level may have played a role in generating the divergent glacial configurations of the northern and southern bank areas.

Keywords:

West Greenland

3D seismic

Contourites

Glacimarine sediments

Continental margin morphology

Glacial isostasy

1. Introduction

Ice streams and outlet glaciers represent the most dynamic components of contemporary and palaeo ice margins in Greenland and Antarctica. These fast-flowing corridors, embedded in the slower moving parts of an ice sheet, exert a major control on glacial discharge (Rignot and Kanagaratnam, 2006; Bamber et al., 2007). This is particularly evident along the central West Greenland coast where Jakobshavn Isbræ, Greenland's largest outlet that discharges into Jakobshavn Isfjord (Fig. 1B), flows at more than 17 km a^{-1} and currently drains c. 6.5 % of the inland ice (Joughin et al., 2004, 2014). A knowledge of the sensitivity and behaviour of past ice streams is crucial for predicting the response of ice sheets to climate warming and its implication for global sea level (Andreassen et al., 2004; Rignot and Kanagaratnam, 2006). An important source of information for understanding ice-ocean-climate interactions comes from studies of ice-marginal processes at the marine limit of outlet glaciers that during past glaciations advanced onto the continental shelves (Stokes and Clark, 2001; Thomas et al., 2011; Nick et al., 2013). Palaeo-ice streams are recognised by large sedimentary fan systems formed at the seaward termini of cross-shelf troughs. These features, known as trough mouth fans (TMFs), are the result of erosion and highly efficient subglacial sediment delivery onto continental slopes during repeated glacial advances (Vorren et al., 1988; Larter and Barker, 1989; Cooper et al., 1991; Vorren and Laberg, 1997; Dahlgren et al., 2005; Nielsen et al., 2005). Distinct geomorphologic signatures of ice stream activity associated with the last glacial cycle may be discerned by a variety of submarine glacial landform assemblages preserved on the seabed of deglaciated continental margins (e.g. Ó Cofaigh et al., 2008; Ottesen and Dowdeswell, 2009; Winsborrow et al., 2010).

This paper presents 3D-seismic data from the shelf adjoining the Disko Bay TMF, one of the largest glacial fan systems in Greenland with sediment thicknesses of up to 2 km (Hofmann et al., 2016; Fig. 1A-B). While previous studies have primarily addressed seabed morphologies preserved within the glacial troughs (e.g. Andreassen et al., 2004; Ó Cofaigh et al., 2008, 2013a; Dowdeswell et al., 2014), this study sheds focus on the relatively little investigated shallow bank areas of the TMF complex (Fig. 1A). To provide a better understanding of these bank areas, the key objectives of this paper are (1) to map and interpret seabed and subsurface geomorphologies, (2) to unravel late Pleistocene ice-sheet configurations and ice-marginal processes, and (3) to place them into context by comparison with other West Greenland glacial outlets as well as regionally with palaeo-ice streams from the Norwegian and the Barents Sea margins.

2. Background

The bathymetry of the central West Greenland margin is influenced by a cross-shelf trough extending for about 370 km from the mouth of Jakobshavn Isfjord to the shelf edge (Fig. 1A-B). The trough is divided into two components by the N-S trending Egedesminde Ridge (depths of 200-300 mbsl) with the deep, narrow Egedesminde Dyb (depths up to ~900 mbsl) to the east and the shallower, broader Disko Trough (depths up to ~600 mbsl) to the west (Fig. 1A). The Disko Trough is delimited by shallow banks, to the north by Disko Banke (water depths of c. 150 m) and to the south by Store Hellefiskebanke (minimum water depths c. 8 m; Weidick and Bennike, 2007). On both banks, a suite of several N – S trending terminal moraine complexes, referred to as Fiskebanke and Hellefisk moraines, mark the limit of previous glaciations (Brett and Zarudzki, 1979; Zarudzki, 1980; Fig. 1A). North of the Disko Trough, a second trough of c. 120 km length, referred to as the Northern Trough (Hofmann et al., 2016; Fig. 1A), branches off the Egedesminde Dyb in a NW direction, reaching water depths of ~500 m on the mid-shelf.

The continental shelf is underlain by large structures and deep basins (Fig. 1A). In the north, the Kangerluk Structure and the Aasiaat Structural Trend formed in consequence of rifting and extensional faulting during the Cretaceous to the Paleocene period (~145–56 Ma; Dam et al., 2009; Gregersen et al., 2013). Late Cretaceous to early Paleocene tectonic reactivation caused uplift and faulting of structural highs, e.g. the Kangerluk Structure (~72–61 Ma; Chalmers and Laursen, 1995; Chalmers et al., 1999). In the south, thrust faulting and compression due to strike-slip movements led to the formation of the Ikermiut Fault Zone and the Ikermiut Basin in Late Paleocene to Early Eocene (~58–48 Ma; Gregersen and Bidstrup, 2008). Subaqueous and subaerial volcanism during the Paleocene and Eocene resulted in basalts being widely spread beneath the shelf. The volcanics crop out at the Egedesminde Ridge and onlap Precambrian gneisses further to the east (Chalmers et al., 1999).

Baffin Bay is a semi-enclosed basin with a predominant cyclonic ocean circulation and a pronounced east-west hydrographic gradient (Fig. 1B). The Baffin Island Current transports cold, low-saline Arctic waters along the Canadian margin that exit through the western Davis Strait. In contrast, the West Greenland Current (WGC) carries warmer (3-5 °C) waters derived from the North Atlantic Irminger Current that advects over the West Greenland shelf regions at water depths of 100-500 m (Bourke et al., 1989; Hamilton and Wu, 2013). Observations of the deep-intermediate circulation of Baffin Bay are sparse but hydrographic modelling indicate a southward counter current along the West Greenland slope from 68 to 72 °N at depths of 1000-1500 m (Tang et al., 2004). At 67 °N, the counter current crosses Baffin Bay to join the southward advection of the Baffin Island Current.

The Disko Bay shelf margin likely became glaciated sometime during late Pliocene – early Pleistocene and hereafter followed several long-term evolutionary stages of TMF accumulation (Hofmann et al. 2016). Based on geomorphological studies offshore and along the coastline of southwest Greenland, Roberts et al. (2009) place the LGM position of the ice margin on the mid-/outer shelf, supposedly associated with the formation of the Hellefisk moraines. Despite the lack of dating and the associated age uncertainty of these shelf-based moraines (Funder et al., 2011), this is consistent with modelling results from Lecavalier et al. (2014). Presence of grounded ice in the Disko Trough during the last glaciation is inferred from streamlined subglacial landforms and tills dated to 12.2 ka BP (Ó Cofaigh et al., 2013a; Jennings et al., 2014). Radiocarbon dates from the Disko Trough and the presence of subtle ridges on the mid-shelf of the modern seabed interpreted as GZWs suggest that glacial retreat was rapid, achieving ice-free conditions on the inner shelf from 12.1 ka BP, corresponding to the Younger Dryas (McCarthy, 2011). It is likely that ice initially retreated to the topographic highs of the Egedesminde Ridge, and the shallow banks - Disko Banke and Store Hellefiskebanke - adjacent to the trough, possibly entailing the formation of the Fiskebanke moraines (Hogan et al., 2012; Ó Cofaigh et al., 2013a; Jennings et al., 2014; Hogan et al., 2016; Fig. 1A). Iceberg scouring on the upper slope suggests that calving tidewater glaciers were established intermittently after the initial glacial retreat (Kuijpers et al., 2007; Hogan et al., 2016). Cosmogenic dating and sea-level data suggest that subsequent recession of the ice margin through Disko Bay occurred rapidly between 10.8-10.1 ka BP (Long and Roberts, 2003; Kelley et al., 2013). Later re-advances of the ice margin at 9.3 and 8.2 ka BP led to the Fjord Stade moraines (Young et al., 2013; Fig. 1B). The rapid, stepwise glacial recessions after the LGM are supported by continuous marine records (Knutz et al., 2013; Jennings et al., in press). These studies suggest that the deglaciation of the Disko Bay region likely occurred under the influence of warm subsurface waters inundating the shelf areas during the Bølling-Allerød and early Holocene. Ice-ocean interactions linked to the WGC have likewise been assigned a key role for the late Holocene climate variability and glacial fluxes from the Disko Bay region (Lloyd et al., 2007; Ouellet-Bernier et al., 2014).

3. Data and methods

The database consists of two 3D-seismic surveys, DW2009-BLK5-3D and DW2009-BLK7-3D, collected by Husky Energy in 2009 covering the outer margin offshore Disko Bay north and south of the Disko Trough (Fig. 1A). The northern survey is located over a shallow bank, hereafter referred to as the Kangerluk Bank, while most of the southern survey is situated along the flank of Store Hellefiskebanke. The seismic grids have a resolution of 25x25 m in the north and 25x12.5 m in the south, respectively. The 3D-seismic data were obtained using a gAS GeoStreamer as recording system for six PGS GeoStreamers with 5760 channels and two three-string Bolt 1900 LLXT air guns as energy source operating with a pressure of 2200 psi. The sampling rate was 2 ms combined with the application of low (4.4 Hz 12 dB/oct) and high cut filters (214 Hz 341 dB/oct). Noise reduction beyond the standard 3-6 low cut filter was unnecessary due to the good quality of data (vertical resolution of 5-10 m in the upper 0.5 s two-way travel-time interval).

For regional bathymetry, the International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0 was applied with contour intervals of 200 m (Jakobsson et al., 2012; Fig. 1A). Multibeam-bathymetric data from within the Disko Trough were used to obtain a more complete and detailed picture of geomorphological features in the Disko Bay shelf region, e.g. grounding-zone wedges within the mid-trough and its fault-bounded northern edge (Hogan et al., 2016; Fig. 1A). The data were collected via a Kongsberg EM120 echosounder at a frequency of 12 kHz and with 191 across-track beams per ping. Gridded cell-sizes comprise 30-40 m. Processing was applied with the MB-System and the Fledermaus software to correct or remove edge artefacts/erroneous data points.

Mapping of seismic key horizons and geomorphological features was carried out following seismic stratigraphic principles (Mitchum et al. 1977). Regional seismic horizons were identified and correlated from earlier interpreted 2D surveys (Hofmann et al., 2016). Age constraints for the onset of glaciation of the Disko Bay margin were provided via the exploration wells Hellefisk-1 and Ikermiut-1 (Hofmann et al., 2016; Fig. 1A). For interpretation of seismic horizons and the generation of two-way travel-time (twt) depth maps, isochore maps, and attribute computation (dip angle), the Petrel seismic interpretation software (version 2014) was used. Seismic inlines and x-lines were interpreted by seeded 3D autotracking and manually with an increment of 10. Depth maps of the seabed were blended with a dip angle relief (smooth: iterations 3, filter width 4) to enhance morphological features of the seismic surfaces. Depth maps of subsurfaces were produced by tracking the peak reflection followed by smoothening (iterations 1, filter width 2). Depth and thickness estimates are denoted in metres below sea level (mbsl) using seismic velocities of 1.85 km s^{-1} (Shipboard Scientific Party, 1987). The same seismic velocities were used for the calculation of sediment accumulation rates (in cm/ka).

4. Results

4.1 Seabed character and features

The seabed mapping results are shown in Figs. 2 – 5, while examples of seismic sections are displayed in Figs. 6 – 8. The northern study area covers the Kangerluk Bank where the bathymetry shallows to about 300 m (Fig. 2). The western part of the bank shows a rugged, hummocky terrain characterized by ridges, sediment mounds and linear erosional features orientated S-SW (Fig. 3A). The shelf margin north-west of the Kangerluk Bank is characterized by a pronounced shelf – slope transition (320-350 mbsl) across a series of distinct topographic steps that cover the upper slope to a depth of about 500 m (Figs. 2, 6A and C). The Kangerluk Bank is bordered to the southeast by a shallow trough (water depths up to 380 m) that is scarred by numerous linear-curvature erosion patterns (Figs. 2 and 3B). To distinguish this feature from the Disko Trough farther south, it is hereafter referred to as the Northern Trough.

The flank of Store Hellefiskebanke, covered by the southern 3D survey, shallows to 180 mbsl in the north-eastern part (Fig. 4). The shallow region (water depths <215 m) is traversed by ridges and pits producing a rugged topography (Figs. 5A-B and 7A-B). Between the area dominated by ridge topography and the shelf edge, the seabed relief is less distinct, although the detailed views reveal numerous incisions and smaller ridges (Figs. 5C-D, 7 and 8). In particular, linear erosional features, oriented NW-SE, are observed that intersect the shelf break (210-240 mbsl) at an oblique angle (Fig. 4). The slope of the study area is characterized by a rather smooth topography to water depths of ~500 m.

Ridges

Three E – W aligned ridges are identified on the Kangerluk Bank (Fig. 3A). The northern and central ridges are characterized by a steep north-facing and the southern ridge by a steep south-facing flank (Figs. 3A and 6A-B). The central ridge is the most prominent one with a mean height of c. 26 m, a length of c. 5.8 km and a mean width of c. 0.8 km, whereas the shallower northern and southern ridges comprise mean heights of c. 8.8 m, lengths of up to 12.7 km and mean widths of 0.5 km.

The flank of Store Hellefiskbanke, at water depths of 150-200 m, is marked by at least seven continuous ridge features, trending in NNW – SSE direction. The spacing between individual segments ranges from 1-4 km with a northward diverging trend (Figs. 5A, 7). In cross-section, the ridges tend to be steepest on the seaward side with dip angles of 4.5-10.5 ° (Fig. 4). Ridge heights and widths vary between 15-25 m and 1.0-1.3 km, respectively, with relief increasing toward southeast as the ridges seem to converge toward the shelf edge. However, the continuation of this trend cannot be verified due to limited data cover. Towards the Disko Trough, the continuous ridges transition into broader mounded features characterized by a subdued relief and a slightly steeper seaward side (Figs. 4 and 5B). They appear more subtle towards the shelf edge, and occasionally overlap the transverse ridges (Fig. 5D). With a spacing that ranges from 5.5-7.5 km, they comprise widths of 2.5-7.0 km and thicknesses of 31-38 m.

A set of smaller linear ridges are identified on the outer shelf in water depths of 200-250 m (Figs. 5C-D, 7A). The ridge complex consists of 6 segments oriented parallel NW-SE along a linear, slightly en-echelon path. The termination of each segment tends to be slightly arcuate in a landward direction. The ridges are on average 3.8 km long, 0.5 km wide and 10 m high.

<u>Anastomosing features</u>

Erosional, anastomosing features are observed along the flank of Store Hellefiskbanke where they incise the mound-ridge topography in a general north-south direction (Figs. 4, 5D). The length of individual channel incisions varies between 3.5 km and 18.0 km, with channel depths/widths up to 20 m and 300 m, respectively. Further seaward towards the outer shelf, the seabed shows signs of erosion in NW – SE direction (Figs. 4, 5C).

<u>Curvilinear features</u>

Cross-cutting curvilinear erosional features are observed in both study areas but are particularly prominent along the south-eastern flank of Kangerluk Bank and the Northern Trough (water depths of 330-390 m; Fig. 3B). The scours trend mostly in a NW – SE direction and are less distinct on the bank itself compared to its flank and the adjacent trough. Individual curvilinear features can be traced for up to 10 km typically terminating in the direction of deeper waters. Erosional depths are generally shallow (e.g. <10 m), while widths may vary between 50-200 m, but the exact dimensions are limited by the resolution of the seismic data.

<u>Scars</u>

These features are seen northeast of the Kangerluk Bank, where four scarp segments (widths of 3-4 km) form the present shelf break toward northwest (Fig. 3C). The scarps display a backstepping character, with an offset decreasing from east to west (from 2.9 km to 1.3 km). The incision of the underlying strata associated with the scarps only seems to affect the most recent sedimentary unit (N-2; Fig. 6C). Further offshore, elongate, arcuate-shaped ridges with alongslope trends are observed in water depths of up to 500 m (Figs. 3C and 6C). The deposits are up to 55 m high. Their steep flank faces south-east, and they comprise lengths between 3.0 km and 3.5 km, and widths between 1.0 km and 1.5 km.

In the south, the shelf edge is incised at an oblique angle by four linear features, which are u-shaped in cross-sections and initiate between 4 km and 7 km landward from the shelf edge (Figs. 5C, 7A and 8B). They extend in a NW – SE direction and widen towards the shelf edge. Their widths range between 0.5 km and 1.0 km and their depths between 8.7 m and 13.0 m.

4.2 Seismic stratigraphy and seismic facies

The investigated stratigraphic interval comprises the two most recent depositional packages of the Disko Bay TMF that were previously described by Hofmann et al. (2016). For the purpose of description and because of differences in depositional character between the study areas, the units are subdivided geographically into N-1 and N-2 (northern area), and S-1 and S-2 (southern area). The corresponding seismic horizons are denoted according to the base of the units, e.g. Base Unit N-1 and Base Unit N-2 (Figs. 6 – 12).

Lower depositional unit (N-1 and S-1)

Horizon Base Unit N-1 has a depth range of 650-1200 ms twt (~600-1110 mbsl) and displays a relatively flat topography over the central parts of the Kangerluk Bank (Fig. 9A). The horizon is marked by erosion, notably seen along the fringes of the shallow bank area (Fig. 9A). Unit N-1 varies in thickness between 40-220 ms twt (~35-200 m) with accumulation focused along the north-western shelf edge (Fig. 9B). Over the Kangerluk Bank, Unit N-1 displays an asymmetric wedge that thins toward the Northern Trough (Fig. 6A). The wedge is characterized internally by uneven lenticular reflections of low to medium amplitudes that downlap onto an erosional base (Base Unit N-1) producing a pattern of low-angle progradation toward SSW (Fig. 6B). Below the Northern Trough, Unit N-1 shows a flat-lying package of thin reflections that onlap horizon Base Unit N-1 (Fig. 6A). The northwest border of the wedge is truncated from a position corresponding to the shelf edge (Fig. 6A and 10A). Below the shelf edge, Unit N-1 displays hummocky, discontinuous reflections juxta-posed to shallow listric faults, while further down-slope, steeply dipping wedges are seen to onlap the Base Unit N-1 horizon (Fig. 6A). These features directly underlie the seafloor area charactized by slide scarps (Fig. 2) suggesting that Unit N-1 forms the oldest part of a mass-transport complex on the north-western margin of the Disko Bay TMF.

Base Unit S-1 ranges between 270-720 ms twt (~250-665 mbsl) and shows a rather rough topography towards the northeast (Fig. 11A). Further seaward in the central part of the dataset, the Base Unit S-1 reflection displays an erosional platform (Fig. 7A), while along its western fringe, a semi-circular trough feature is revealed (Fig. 11A-B). The trough seems to be in close relation to the underlying pre-glacial structures, with the Ikermiut Basin located directly below and fault-bounded to the east along the Ikermiut Fault Zone (Fig. 1A). Unit S-1 shows thickness variations between <50-400 ms twt (~45-370 m) with a large depocentre at the location of the trough (Fig. 11B). The unit consists of a thick sedimentary package with low-angle progradation towards the southwest (dip angles of 0.8-1.3 °) and is affected by topset truncation (Fig. 7A-B). Reflection geometries reveal several internal unconformities that bear an erosional signature (Fig. 7B). Channel features are commonly observed in the central part of the survey encompassing an area of c. 43 km^2. The seismic resolution sporadically enables mapping of the channels that generally trend in a N – S direction, with average lengths of c. 4 km, widths of c. 0.7 km and depths of c. 35 m (Fig. 7B).

Upper depositional unit (N-2 and S-2)

Base Unit N-2 reveals a depth range of 510-1230 ms twt (~470-1135 mbsl) and a flat, shallow topography over Kangerluk Bank (Fig. 10A). Unit N-2 has a thickness of c. 110-120 m over Kangerluk Bank that increases to c. 130 m along the outer north-western margin and to >230 m within the Northern Trough, respectively (Fig. 10B). It comprises aggradational stratified deposits over the Kangerluk Bank area (Fig. 6A and B), whereas the upper-slope section is characterized by mounded aggradational geometries (Fig. 6C) that extend over c. 23 km along the NW margin (Fig. 10B), onlapping the basal reflection of Unit N-2.

The Base Unit S-2 horizon comprises depths of 275-725 ms twt (~255-670 mbsl; Fig. 12A) and, along the outer margin to the west, two curvilinear furrows are revealed (Figs. 8A and 12). They occur in a NW – SE direction, with terminations towards the SE. The features are c. 5 km long and comprise widths of c. 238 m and depths of c. 10 m. Unit S-2 thicknesses range between <25-200 ms twt (~25-185 m) with two depocentres along the outer south-western margin (Fig. 12B). To the west, the modern shelf break displays a pronounced character and the upper part of the unit is characterized by a low amplitude, discontinuous microscale progradational signature towards the SW, with downlap on the basal part (Fig. 8A). This is in contrast to the east, where the modern shelf break becomes less distinct and the unit comprises low amplitude, mounded aggradational reflection geometries that onlap onto the Base Unit S-2 horizon (Fig. 8B).

5. Discussion

5.1 Interpretation of sedimentary products and processes

5.1.1 Grounding-zone wedges

Asymmetric sedimentary wedges similar to the seismic geometries of Unit N-1 on Kangerluk Bank (Fig. 6A-B) have previously been described from the NW Greenland (Dowdeswell and Fugelli, 2012) and Antarctic glaciated margins (Alley et al., 2007). These deposits, referred to as grounding-zone wedges (GZWs), are typically developed with internal lenticular bedforms that dip in the direction of ice flow, typically into deeper waters. GZWs are thought to form at the grounding zone below ice margins that are temporarily stagnant and, to build up a wedge of dimensions as within Unit N-1, sufficient accommodation space and high sediment yields are required (Alley et al., 1986, 2007; Dowdeswell and Fugelli, 2012). Similarly, even though they are smaller scale features, the asymmetric seabed geometries of the northern and southern ridges on Kangerluk Bank, and the broad mounded ridges along the flank of Store Hellefiskebanke are interpreted as GZWs (Figs. 3A and 5B).

5.1.2 Terminal moraines and remnant ice deposits

The seabed morphology along the flank of Store Hellefiskebanke is marked by multiple sets of semi-parallel ridges interpreted as terminal moraines (Figs. 5A and 7A-B). Similar features have been observed on other glaciated margins and are generally related to a slow and stepwise retreat of active, grounded ice from its LGM position on the outer shelf (e.g. Dowdeswell et al., 2008; Ottesen and Dowdeswell, 2009; Winsborrow et al., 2010).

On the seabed of Kangerluk Bank, the central ridge oriented parallel to the former ice-flow direction from E to W, combined with randomly arranged hummocky features, is reminiscent of a zone that represents the product of the melt-out of stagnant, debris-covered dead-ice (Schomacker, 2008; Figs. 3A and 6A-B).

5.1.3 Meltwater related features and products

Reflection discontinuities observed within the upper part of Unit S-1 south of a semi-circular infilled trough (Fig. 7B) and erosional channel features on the seabed along the flank of Store Hellefiskebanke (Fig. 5D) are interpreted as subglacial meltwater channels or small tunnel valleys. These features indicate a high-energy flow of excess meltwater that is unable to drain through the glacial bed (Noormets et al., 2009; Van der Vegt et al., 2012). It is likely that the trough depocentre (Unit S-1; Fig. 11B) was infilled by sediments brought by subglacial drainage.

5.1.4 Slope instability and mass-transport deposits

Back-stepping scarps on the seabed along Kangerluk Bank are suggestive of slide scars that were created as a result of erosional mass movement induced by instabilities along the north-western slope. Further downslope, slide deposits in the form of arcuate ridges are interpreted as pressure ridges that indicate a composition of cohesive material (García et al., 2012; Casalbore et al., 2016; Figs. 3C and 6C).

Seabed incisions interpreted as gullies are apparent below the shelf break along the flank of Store Hellefiskebanke at present water depths of 230-270 m (Figs. 5C and 8B). In general, gully formation is assigned to various mechanisms along high-latitude continental margins, such as mass-flow erosion due to gas-hydrate dissociation or due to efficient glacial accumulation along the outer margin, tidal pumping beneath ice shelves, alongslope bottom-currents, or dense brine plumes (e.g. Vorren et al., 1988; Noormets et al., 2009; Gales et al., 2013a).

5.1.5 Submarine currents and icebergs

Mounded aggradational deposits, which construct the outer margin of both Units N-2 and S-2, are interpreted as contourite drifts (e.g. Faugères and Stow, 2008; Knutz et al., 2015; Figs. 6C and 8B), consistent with results by Hofmann et al. (2016), who assigned alongslope bottom-currents a major role in sedimentation along the outer Disko Bay margin.

Based on their geometrical appearance and distal marginal setting, we assign the arcuate-shaped ridges on the seabed along the flank of Store Hellefiskebanke (Figs. 5C-D and 7A) either to De Geer moraines that are generated at marine-terminating ice-sheet margins, as previously described for northern Sweden (Lindén and Möller, 2005), or to current-influenced sand bars, e.g. by longshore or rip currents (cf. Bowen, 1969; Castelle et al., 2016). When breaking waves hit the shoreline at a normal angle, longshore currents are generated in the surf zone that converge to an offshore flow, the rip current. Rip currents play an important role in sediment transport and in shaping the coastline (MacMahan et al., 2006, Winter et al., 2014).

Based on their geomorphological appearance (cf. Woodworth-Lynas et al., 1991; Dowdeswell and Ottesen, 2016; Lewis et al., 2016), curvilinear incisions identified along the outer margin of Base Unit S-2 and on the seabed along the flank of Kangerluk Bank are interpreted as iceberg ploughmarks (Figs. 3B, 8A and 12A), i.e. the product of icebergs drifting with ocean currents and simultaneously scouring the seafloor.

5.2 Late Quaternary ice-sheet configurations and shelf margin processes

The interpretation of palaeo-ice sheet configuration, glacial drainage patterns and marine current regimes applying to the two seismic units and the seabed is shown in Fig. 13.

5.2.1 Lower seismic unit (N-1 and S-1)

The presence of relict grounding-zone deposits on Kangerluk Bank suggests that ice became established at the shelf edge during a major advance stage prior to the last glacial cycle (Fig. 13A). Topset truncation of clinoform reflections in the seaward westernmost part of the GZW (Fig. 6B) indicates that, at some point, subsequent to formation of the wedge, the shelf margin was overridden by heavy grounded ice. This major glacial advance was likely associated with the presence of a 200 m deep palaeo-trough bordering the southern edge of the Kangerluk Bank GZW (Northern Trough in Fig. 6A and 10A). The smooth trough relief and preservation of horizontal sediment layers below the trough, presumably representing fine-grained deposits, point to a highly dynamic and largely non-erosive ice stream that likely extended north of the main Disko Trough (NT in Fig. 1A).

The semi-circular trough bordering Store Hellefiskebanke (Fig. 11A-B) is ascribed to a southern drainage route on the outer Disko Bay TMF circumventing Store Hellefiskebanke (Hofmann et al., 2016; Fig. 13A). The location of this drainage route is associated with the underlying pre-glacial Ikermiut Basin that accommodates thick packages of glacigenic deposits. In addition, zones of weakness linked to N – S trending fault structures along the Ikermiut Fault Zone possibly fostered glacial drainage into the basin. Similar observations have been made in the Amundsen Sea Embayment, West Antarctica, where ice-stream discharge was facilitated by pre-existing fault systems (Gohl, 2012). The occasionally channelized sediments infilling the trough suggest that the southern sector of the Disko Bay TMF was meltwater prone during the formation of Unit S-1. In combination with low-angle progradation toward southwest (Figs. 7A and 8A), this indicates a highly dynamic subglacial regime with potentially fast-flowing ice streams reaching the shelf edge west of Store Hellefiskebanke (Larter and Barker, 1989; Cooper et al., 1991; Barker, 1995; Fig. 13A) in consistency with regional mapping (Hofmann et al., 2016).

The two uppermost seismic units probably reflect the late Pleistocene – Holocene development of the Disko Bay TMF but the exact chronology is unknown due to the lack of long core records. Hence, a preliminary chronology can only be inferred by correlation to terrestrial record. The conditions sustaining GZW accumulation and progradation within the lowermost seismic interval (Units N-1 and S-1) are likely related to a prolonged glacial period with sea levels fluctuating around a low mean. Previous studies have suggested that the Greenland Ice Sheet was more extensive during the penultimate glacial period (Saalian) than during the LGM (Weidick and Bennike, 2007; Funder et al., 2011) with coastal nunataks in the Sisimiut area of West Greenland being ice-covered (Roberts et al., 2009). Assuming that the buried units on both bank areas are correllatable, e.g. can be ascribed to similar geological ages, it is possible that they formed during the penultimate glaciation (Saalian). Ascribing an early Saalian glacial age of 340 ka BP to the Base Unit N-1 and S-1 horizons, results in maximum sediment accumulation rates of 95-176 cm/ka. Despite the high uncertainty, primarily linked with the unit chronology, these values are consistent with sedimentation rates from glaciated margins at similar latitudes, such as the UK margin where rates of 2 m/ka have been estimated for the lower Barra Fan during MIS 2 (Knutz et al., 2001).

5.2.2 Upper seismic unit (N-2 and S-2)

The GZW below the Kangerluk Bank is covered by onlapping aggradational strata of Unit N-2 that infill the buried component of the Northern Trough (Figs. 1A and 6A). Planar erosion over the GZW and a strong reflection below the trough (Base Unit N-2) indicate that a glacial shelf edge advance occurred prior to the southward shift in the focus of deposition. The 150 m thick stratified cover over the GZW, interpreted as glacimarine sediments, points to high sediment fluxes under submarine conditions, i.e. turbid meltwater plumes produced during one or more deglacial retreat stages. The deposition of these thick glacimarine sediments, largely preserved from subsequent erosion, suggests that Kangerluk Bank was covered by floating ice, possibly forming part of an ice shelf extending farther into Baffin Bay (Fig. 13B). The floatation stage was probably associated with a relative increase in sea-level.

Horizon Base Unit S-2 forms a seaward tilting palaeo-slope surface that crops out towards the northeast along the flank of Store Hellefiskebanke (Figs. 7A and 8A-B). The horizon is marked by widespread glacial erosion, while, towards southwest on the outer margin it appears smoother, with sporadic incisions interpreted as iceberg ploughmarks (Figs. 8A and 12A-B). This indicates that the slope section of Base Unit S-2 was influenced by glacimarine processes. Unit S-2 displays two depocentres below an erosional shelf break on the outer margin southwest of Store Hellefiskebanke (Fig. 12B). Progradation of small, steeply dipping clinoforms within the upper part of the main accumulation (up to 150 m thick) indicates a glacial advance to a position below the modern shelf break (Figs. 8A and 12B). The clinoform deposits are obscured by the seabed reflection but may represent debrites formed in front of an advancing ice stream (e.g. Vorren et al., 1988; Vorren and Laberg, 1997). A more dispersed and elongate depocentre extends southeastward along the slope (Fig. 12B). It is characterized by aggradational convex reflections that downlap/onlap onto the slope but minor clinoform signatures are also seen (Fig. 8B). The complex seismic facies of the elongate body and its juxtaposition to a small glacial depocentre suggest that it may form a mixed system of shelf progradation and contourite deposition. The feature indicates that alongslope currents, presumably related to a southward flowing counter-current (Fig. 1B) have influenced the recent development of the outer Disko Bay TMF (Figs. 6C, 8B and 12B), pointing to fully marine and ice-distal conditions in this area (Fig. 13B). The thickness of the Unit S-2 depocentres and the inferred maximum sedimentation rates of 142 cm/ka (see below) imply that sediment transport to the outer margin was very efficient, requiring fast-flowing ice accommodated by wet-based conditions and high meltwater fluxes (Stokes and Clark, 2001). Presumably, sediments were mainly fine-grained, generated by meltwater plumes or low-energy turbidity flows (Rashid et al., 2003). The linkage between ice-sheet instability and marine subsurface warming, e.g. evident by basal melting of floating ice shelves, has been emphasized in several studies (e.g. Knutz et al., 2011; Moros et al., 2016). The flow of northward-directed subsurface currents bringing warmer waters to the ice grounding line was likely important for maintaining the dynamic glacial regime and probably an important factor for the glacimarine conditions that were established during the most recent evolutionary phase of the Disko Bay TMF (Units N-2 and S-2).

Marine deposits referred to as the Svartenhuk stage have been identified in central West Greenland coastal sections, and assigned to the Last Interglacial period (MIS 5) based on faunal and amino acid analyses (Bennike et al., 1994). The Svartenhuk marine event is associated with reduced ice volumes and global sea levels 3-5 m higher than present, based on ice-core data and climate models (Cuffey and Marshall, 2000; Huybrechts, 2002; Otto-Bliesner et al., 2006). Thus, it is feasible that the contourite units seen in the lower part of the uppermost seismic unit (N-2 and S-2; Figs. 6C and 8B) could have formed during the Eemian interglacial when higher-than-present sea levels would allow a larger flux of surface-intermediate water masses to pass along the outer shelf and upper slope (Fig. 13B). Similar conditions may have applied during the warm interstadial phases of MIS 5 and MIS 3, although with sea levels 25-60 m lower than present (Spratt and Lisiecki, 2016). Sediment accumulation rates, based on an assumed age of 130 ka for the Base Unit N-2 and Base Unit S-2 horizons, range from 142-177 cm/ka within the upper seismic unit. These rates appear relatively high but are reasonable for a shelf margin glacimarine setting, as described for the south Vøring margin (sediment accumulation rates of about 100 cm/ka; Hjelstuen et al., 2004). Although the age relationships of the Late Quaternary units of the outer Disko Bay margin remain speculative, they are consistent with the interpretation that the most recent depositional phase was influenced by glacimarine sedimentation, localized shelf-edge ice advances and sediment transport by contour currents. These conditions contrast the evidence for major glacial advances to the shelf margin associated with the lowermost unit, possibly formed during the Saalian glaciations.

5.2.3 Seabed features

The seabed on Kangerluk Bank reveals ablation products from grounded passive ice possibly of deglacial age (Fig. 13C), i.e. subsequent ice collapse and melting resulted in the formation of remnant-ice features, superimposed upon a GZW draping the western bank area (Fig. 3A). The following ice-sheet retreat probably occurred quickly with only one major stillstand on the ice-proximal topographic high of Disko Banke. In the absence of erosive features relating to streaming ice, we suggest that a floating ice shelf, associated with the stratified deposits of Unit N-2, became grounded on Kangerluk Bank. A late glacial/deglacial grounding event seems counter-intuitive considering the eustatic sea-level rise that occurred after 17 ka BP (Lambeck and Chappell, 2001) which would increase sea levels and offset grounding. It is possible, however, that the ice-grounding phase was relating to a brief period during the last deglaciation when isostatic uplift may have outpaced eustatic sea-level rise. This interpretation is supported by Bennike et al. (2002) who show that, in South Greenland, lake basins emerged above sea level due to isostatic uplift after the deglaciation at 13.8 cal ka BP. Although the cause of the inferred ice-shelf grounding is uncertain, substantial seabed faults observed along the northern edge of the modern Disko Trough (Fig. 1A; Hofmann et al., 2016) and the pervasive presence of slides on the northern slope (Figs. 3C and 6C) suggest that this part of the margin may have been particularly prone to neotectonic adjustments. Similar to the Base Unit N-2 reflection, the seabed displays imprints of a northern ice lobe (cf. Northern Trough; Figs. 1A, 6A and 13C) that has retreated further landward since the deposition of Unit N-2. As for the buried trough component, a lack of significant erosion within the modern trough may suggest that ice-flow dynamics were mainly controlled by external conditions, e.g. the vicinity to the West Greenland Current and the presence of marine muddy sub-strata on the outer margin forming surge-prone subglacial conditions (Alley et al., 1989c).

The terminal moraine ridges appear to be part of the Hellefisk moraines (Figs. 5A and 13C) that have been assigned to either the Saalian (Kelly, 1985) or the LGM (Roberts et al., 2009). The moraines have not been dated yet but the fact that the Disko Ice Stream was affected by a major stillstand period on the mid-shelf after retreat from the outer shelf at 12.2 ka BP (Ó Cofaigh et al., 2013a; Jennings et al., 2014; Hogan et al., 2016) is consistent with the moraine location along the flank of Store Hellefiskebanke (Fig. 13C), suggesting a calving-bay configuration and an age for the moraines not older than the LGM. Alternatively, the Hellefisk moraines may represent complex structures that may have been built up during several different stages. Thus, further research is needed to better understand the complexity of this morainal system on the mid-/outer margin. The transition from terminal moraines into patchy GZWs along the western fringe of the 3D survey (Figs. 5B) indicates a lateral shift in ice-sheet configuration, i.e. from grounded ice conditions in the south where deposition of glacial sediments mainly occurs in front of the ice margin, to predominantly floating ice conditions towards the Disko Trough with subglacial sediment accumulation into ice-shelf cavities at the grounding zone (Alley et al., 1986; Dowdeswell and Fugelli, 2012). The spatial transition in landform distribution presumably relates to the increasing water depth with increasing proximity to the Disko Trough where the ice would have been more prone to decoupling from its bed. Isostatic and tectonic influences on relative sea level may have played a role in generating the divergent glacial configurations on Kangerluk Bank and along the flank of Store Hellefiskebanke (Fig. 13C). The influence of sea level is also reflected by the differences in modern water depths with ~300 m over Kangerluk Bank compared to ~150-200 m along the flank of Store Hellefiskebanke (Fig. 1A).

The slide scars and lobate seismic geometries observed on the northern slope area (water depths of 330-390 m) indicate a dominance of mass transport processes beyond the present shelf break (Figs. 3C and 6C). The disturbances caused by the slides are largely confined to surficial sediments (not covered by younger sediments) and do not affect deeper sedimentary packages, thus inferring a recent age. Slope failures can be induced by a wide range of factors, e.g. iceberg grounding, high sedimentation rates and depositional oversteepening, or post-glacial slope instability due to tectonic adjustments (García et al., 2012). However, the back-stepping scarps along Kangerluk Bank have a distinct appearance and their location coincides with underlying structural boundaries of the Kangerluk Structure and the Aasiaat Structural Trend (Fig. 1A). Hence, it is possible that these structural elements have facilitated neotectonic adjustments that subsequently may have triggered the slide events during the deglaciation period.

We assume that gully formation on the Disko Bay margin is linked to sediment-laden meltwater flows that drained the grounded ice margin on the outer shelf (Noormets et al., 2009). Evidence for this hypothesis can be found along the transverse moraine ridges further landward, where erosional, anastomosing channel features can be seen (Figs. 5D), indicative of focused, high-energy flow activity. In common with the gully features, these channels generally trend in a NNW/NW – SSE/SE direction, presumably in order to circumvent a grounded paleo-ice margin. Seabed erosion, observed further offshore and likely associated with meltwater flow as well (Figs. 5C), shows a similar orientation establishing a connection between the channel and the gully features. The spatial association between the drainage elements and the transverse moraine ridges suggests that these features formed during the same glacial stage, and considering the freshness and uniform direction of the drainage features, this is likely to be the LGM (Fig. 13C).

Iceberg ploughmarks observed along the south-eastern flank of Kangerluk Bank, at water depths of 330-390 m, indicate predominantly ice-distal conditions in this area (Fig. 3B). The scours generally show a NW – SE trend and pinch out in deeper water towards the south. Similarly, iceberg ploughmarks observed along the flank of Store Hellefiskebanke towards the shelf edge (Figs. 7B and 8A) also trend in NW – SE direction, but at much shallower water depths of 210-225 m. Source areas may either be the Kangerluk Bank, with its presumably “lightly” grounded ice/ice-shelf configuration, or local ice streams on the Disko Bay margin, where glacial retreat may have resulted in the formation of a calving bay over the inner trough (Hogan et al., 2016; Fig. 13C), providing a cross-shelf route for iceberg drift. However, sources related to glacial outlets farther to the south cannot be ruled out considering the prominent influence of northward contour currents along the shelf margin (Hofmann et al., 2016). After the last glacial period, drift directions of icebergs offshore of Disko Bay seem to be controlled by the influx of North Atlantic waters, consistent with a study from Sheldon et al. (2016) who showed that the West Greenland Current was established before 14 ka BP. Although the ploughmarks on the outer shelf appear relatively fresh, it is unlikely that they represent traces of modern icebergs, considering that waters in this area are relatively deep (210-390 mbsl) and icebergs calving from Jakobshavn Isbræ would first have to cross the much shallower Egedesminde Ridge (water depths of ~200 m) in order to enter the outer shelf (Fig. 1A). Consequently, we infer that these features were formed during the early stage of the last deglaciation before the ice stream retreated eastward of the Egedesminde Ridge at c. 10.9 cal ka BP (Jennings et al., 2014) and when sea-levels were still relatively low.

5.3 Comparison with other ice streams

Based on evidence of a thin till deposit in a core from the outer Disko Trough and the presence of GZWs traversing within the central parts of the Disko Trough, it was suggested that grounded ice extended to the shelf edge during the Younger Dryas (Ó Cofaigh et al., 2013a; Jennings et al., 2014; Hogan et al., 2016; Fig. 13C). Seabed studies from the Melville Bay region (Fig. 1B) likewise suggest that ice streams draining the northern Greenland Ice Sheet where fast-flowing and fully grounded during glacial maximum phases leaving distinct and widespread traces of MSGLs (Slabon et al. 2016; Newton et al., 2017). Seabed morphologies, e.g. narrow trough lacking evidence of intensive erosion and the preservation of fault scarps, as well as accumulation patterns of the Disko Bay TMF suggest that glacial dynamics were very different compared to the neighbouring Uummannaq TMF and the troughs in NE Baffin Bay (Fig. 1B). Several factors may explain the contrasting patterns of trough morphologies and glacial erosion expressed by the modern West Greenland TMFs. However, a key control relates to the topographic ridge that extends south of Disko (Egedesminde Ridge) which impedes direct ice flow out of Disko Bugt. The Egedesminde Ridge and the prevalent shallow banks on the outer margin, controlled by underlying geological structures, form multiple grounding zones that can buttress a major ice shelf (Hofmann et al., 2016). A floating ice shelf that presumably covered the vast shelf region during peak glacial periods would be prone to basal warming driven by marine subsurface currents (Oppenheimer, 1998). However, in comparison with the TMFs to the north (Fig. 1B), with troughs up to 80 km broader and 820 m deeper, an ice shelf over the Disko Bay margin would be less exposed to basal melting and thus likely more stable.

The GZWs located within the Disko Trough and along the flank of Store Hellefiskebanke play an important role for the understanding of the retreat history of West Greenland ice streams. Similar topographic stability points are seen in the Uummannaq and Melville Bay troughs in the form of mid-shelf GZWs (Dowdeswell et al., 2014; Slabon et al., 2016). Their formation has been related to Younger Dryas cooling (Sheldon et al., 2016; Slabon et al., 2016; Newton et al., 2017). However, these topographic features are an order of magnitude smaller than the Egedesminde Ridge. We conclude that local topography controlled by the underlying geological and tectonic setting is of major significance for imparting differences in glacial-dynamic regimes of neighboring TMF systems.

In common with the West Greenland margin, the Norwegian shelf region from 57°N to 80°N has revealed a dynamic glacial history during the late Pleistocene period. Numerous cross-shelf troughs show signs of mega-scale glacial lineations (MSGLs), indicative of fast-flowing ice streams (Ottesen et al., 2005). Findings of MSGLs can provide valuable information on maximum extents of grounded ice, e.g. in Vestfjorden, Trænadjupet and Sklinnadjupet where ice streams appear to have reached the shelf edge several times during late Pleistocene glaciations. Orientations of MSGLs, representative of former ice-flow directions, give evidence that ice streams in Vestfjorden and Trænadjupet were affected by flow switching during the last glacial period (Ottesen et al. 2005), as ice flow was probably westward directed during the penultimate Saalian and subsequently turned southward during the most recent glaciation (Dowdeswell et al. 2006). The Late Weichselian ice flow switching may have been induced by a lack of accommodation space, as sediment accumulations from previous glacial periods increasingly impeded ice flow towards the west. As a result, a new 150 m-deep glacial trough was carved into the shelf sediments. Similar to West Greenland ice streams, ice streams along the Norwegian margin confirm the significance of topographic settings on glacial configurations and flow directions (Dowdeswell et al., 2006).

Ice flow switching has also been observed within the Bear Island Trough along the Barents Sea margin, where numerous MSGL flow sets were overprinted due to asynchronous ice stream activity during deglaciation of the Barents Sea Ice Sheet, possibly induced by the migration of ice divides and catchment areas. Ice stream behavior in this case may have been largely controlled by a varying grounding line bathymetry. Glacial retreat from the shelf edge may have been initiated by eustatic sea level rise, and subsequently, topographic controls may have been a crucial factor in the gradual grounding line retreat (Patton et al., 2015).

6. Conclusions

Geophysical data from banks adjoining the Disko Trough suggest different glacial regimes along the studied margin segment during the late Pleistocene (Fig. 13), emphasizing the role of local factors as ice dynamics, topography and tectonics in its development. The main conclusions from this study are:

- The Saalian period (lower seismic unit) was characterized by major glacial advances to the shelf margin (Fig. 13A) indicated by a relict GZW on Kangerluk Bank and low-angle progradation observed along the flank of Store Hellefiskebanke.
- The Eemian (upper seismic unit) was influenced by glacimarine sedimentation, localized shelf-edge ice advances and sediment transport by contour currents (Fig. 13B).

- During the last (de)glaciation, Kangerluk Bank appears appears to have been covered by passive ice leaving a field of dead-ice deposits.
- The seabed along the flank of Store Hellefiskebanke reveals multiple sets of terminal moraine ridges indicating a slow retreat of active, grounded ice from the Last Glacial Maximum position on the outer shelf toward Store Hellefiskebanke.
- Isostatic and tectonic influences on relative sea level may have played a role in generating the divergent glacial configurations on Kangerluk Bank and along the flank of Store Hellefiskebanke (Fig. 13C).
- We conclude that local topography controlled by the underlying geological and tectonic setting is of major significance for imparting differences in glacial-dynamic regimes of neighboring TMF systems and for evaluating ice stream behaviour along other formerly glaciated margins, e.g. the Norwegian and the Barents Sea margins.

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Figure captions

Fig. 1: Overview of the central West Greenland margin. (A) Bathymetric map of the Disko Bay TMF system, with exploration wells Hellefisk-1 and Ikermiut-1. Based on IBCAO (Jakobsson et al., 2012) with 200 m contour intervals. Multibeam swath bathymetry from the Disko Trough is based on Hogan et al. (2016). Structural elements are outlined in grey (modified after Gregersen and Bidstrup, 2008). The location of the Fiskebanke/Hellefisk moraine system is displayed in light green (Weidick and Bennike, 2007). 3D-seismic datasets Husky-DW2009-BLK5-3D north and Husky-DW2009-BLK7-3D south of the Disko Trough are displayed in red. Profiles highlighted with blue are shown in Figs. 6 – 8. ED = Egedesminde Dyb, ER = Egedesminde Ridge, DT = Disko Trough, NT = Northern Trough, DIC = Disko Island Channel, HB = Store Hellefiskebanke, DB = Disko Banke, KB = Kangerluk Bank, IB = Ikermiut Basin, IFZ = Ikermiut Fault Zone, AST = Aasiaat Structural Trend, KS = Kangerluk Structure, HM = Hellefisk moraines, FBM = Fiskebanke moraines. (B) Ocean circulation in Baffin Bay (modified after Curry et al., 2011). JI = Jakobshavn Isfjord, FSM = Fjord Stade moraines, DI = Disko Island, DBTMF = Disko Bay Trouth Mouth Fan, UTMF = Uummannaq Trough Mouth Fan, MBTMF = Melville Bay Trough Mouth Fan, EGC = East Greenland Current, IC = Irminger Current, WGC = West Greenland Current, CC = Counter Current, BIC = Baffin Island Current.

Fig. 2: Regional seabed geomorphology constructed from the northern 3D dataset. Position of 3D-seismic lines displayed in Fig. 6A – C is shown in blue and red, respectively. Black rectangles outline the location of prominent geomorphic features (Fig. 3A – C). Black stippled line marks the shelf break. KB = Kangerluk Bank, NT = Northern Trough. Shaded depth map in metres below sea level (mbsl; using v_P = 1.5 km s^{-1}) with illumination from the NW, underlain by a dip angle relief. The dip angle relief was smoothened using 3 iterations and a filter width of 4.

Fig. 3: Examples of submarine landforms preserved on the outer margin north of the DT (see Fig. 2 for location). (A) E – W trending ridge features are interpreted as dead-ice feature (cf. dashed rectangle labelled as dead-ice zone) and grounding-zone wedge (GZW), respectively. (B) Iceberg ploughmarks on the outer shelf. (C) Along the NW shelf edge, slope instabilities have led to mass movement as shown by the back-stepping slide scars.

Fig. 4: Regional seabed geomorphology constructed from the southern 3D dataset. Position of 3D-seismic lines displayed in Figs. 7A-B and 8A-B is shown in red and blue, respectively. Black rectangles outline the location of prominent geomorphic features (Fig. 5A – D). Black stippled line marks the shelf break. HB = Store Hellefiskebanke. Shaded depth map in metres below sea level (mbsl; using vp = 1.5 km s^{-1}) with illumination from the SW, underlain by a dip angle relief. The dip angle relief was smoothened using 3 iterations and a filter width of 4.

Fig. 5: Examples of submarine landforms preserved on the outer margin south of the DT (see Fig. 4 for location). (A) A suite of moraine ridges which are interpreted to mark the maximum extent and subsequent retreat of the Late Weichselian Greenland Ice Sheet. (B) Possible grounding-zone wegdes (GZWs) towards the Disko Trough mark the grounding zone of an ice stream or ice shelf during a temporary stillstand. (C) The NW – SE trending ridges are interpreted as sand bars possibly deposited by longshore currents in a marine setting. Gullies incising the shelf edge record erosive downslope sediment transport. (D) The presence of GZWs partly incised by well-preserved meltwater channels suggests a transition from the grounding line to the grounding-line proximal environment during the course of deglaciation.

Fig. 6: Seismic profiles located over a shallow bank north of the DT (see Fig. 1A for line positions), are depicted with interpreted key horizons of the late TMF stage. Black arrows indicate prominent geomorphic features. NT displays the Northern Trough. (A) and (B) outline a buried grounding-zone wedge (GZW). (C) The scarps, combined with ridge features and infilling deposits further downslope, are related to sliding along the slope.

Fig. 7A-B: Seismic profiles located over a shallow bank south of the DT (see Fig. 1A for line positions) are depicted with interpreted key horizons of the late TMF stage. Red circle indicates modern shelf break. Black arrows indicate prominent geomorphic features, e.g. a suite of moraine ridges on the outer shelf and a contourite drift complex along the shelf edge and slope. Close-up of Fig. 7B displaying reflection discontinuities reminiscent of subglacial channel features in the central part of the survey.

Fig. 8: Examples of seismic facies and detailed geometries associated with submarine and/or glacial processes (see Fig. 1A for line positions). (A) Seismic profile across the outer margin at the western edge of the southern survey showing microscale progradation and downlap. Note the rough seafloor topography due to iceberg carving. (B) Seismic profile across the outer margin of the southern survey showing slope deposits of aggradational character that onlap the Base Unit S-2 horizon. The seabed is incised by channel-like features interpreted as gullies.

Fig. 9: Regional geomorphology of the Base Unit N-1 sub-surface constructed from the northern 3D dataset. Position of 3D-seismic lines displayed in Fig. 6A – C is shown in blue and red, respectively. Black stippled line marks the palaeo-shelf break. KB = Kangerluk Bank, NT = Northern Trough, GZW = grounding-zone wedge. (A) Shaded depth map in two-way travel time

(twt) with illumination from the NW. The depth map was smoothened using 1 iteration and a filter width of 2. (B) Isochore map of the Base Unit N-1 – Base Unit N-2 interval in two-way travel time comprising a relict GZW.

Fig. 10: Regional geomorphology of the Base Unit N-2 sub-surface constructed from the northern 3D dataset. Position of 3D-seismic lines displayed in Figs. 6A – C is shown in blue and red, respectively. Black stippled line marks the palaeo-shelf break. KB = Kangerluk Bank, NT = Northern Trough, GZW = grounding-zone wedge. (A) Shaded depth map in two-way travel time (twt) with illumination from the NW. The depth map was smoothened using 1 iteration and a filter width of 2. (B) Isochore map of the Base Unit N-2 – Seabed interval in two-way travel time.

Fig. 11: Regional geomorphology of the Base Unit S-1 sub-surface constructed from the southern 3D dataset. Position of 3D-seismic lines displayed in Figs. 7A-B and 8A-B is shown in red and blue, respectively. Black stippled line marks the palaeo-shelf break. HB = Store Hellefiskebanke. (A) Shaded depth map in two-way travel time (twt) with illumination from the SW. The depth map was smoothened using 1 iteration and a filter width of 2. (B) Isochore map of the Base Unit S-1 – Base Unit S-2 interval in two-way travel time.

Fig. 12: Regional geomorphology of the Base Unit S-2 sub-surface constructed from the southern 3D dataset. Position of 3D-seismic lines displayed in Figs. 7A-B and 8A-B is shown in red and blue, respectively. Black stippled line marks the palaeo-shelf break. HB = Store Hellefiskebanke. (A) Shaded depth map in two-way travel time (twt) with illumination from the SW. The depth map was smoothened using 1 iteration and a filter width of 2. (B) Isochore map of the Base Unit S-2 – Seabed interval in two-way travel time. The western depocentre along the shelf edge and slope is

derived from accumulation of progradational sediment packages after their subglacial transport towards the slope, while the depocentre to the east is associated with a contourite drift complex that has been deposited by alongslope bottom-currents.

Fig. 13: Deglacial model for the outer Disko Bay margin illustrating ice-flow patterns and ice-margin positions. The IBCAO bathymetric map (Jakobsson et al., 2012) with 200 m contour intervals is overlain by multibeam swath bathymetry from the Disko Trough (Hogan et al., 2016) and depth maps from the bank areas. The regional depth maps were constructed by Hofmann et al. (2016). The location of the Fiskebanke/Hellefisk moraine system is displayed in light green (Weidick and Bennike, 2007). White solid lines indicate the position of a thin and rather passive ice margin. White stippled lines delineate the maximum extent of a dynamic and active ice margin during a major stillstand period. ED = Egedesminde Dyb, ER = Egedesminde Ridge, DT = Disko Trough, NT = Northern Trough, GZW = grounding-zone wedge, HB = Store Hellefiskebanke, DB = Disko Banke, KB = Kangerluk Bank, HM = Hellefisk moraines, FBM = Fiskebanke moraines, WGC = West Greenland Current. (A) The Saalian period was characterized by major glacial advances to the shelf margin. (B) The Eemian was influenced by glacimarine sedimentation, localized shelf-edge ice advances and sediment transport by contour currents. (C) During the final stage of glaciation, Kangerluk Bank appears to have been influenced by grounding of thin and rather passive ice, whereas the flank of Store Hellefiskebanke reveals multiple sets of transverse moraine ridges indicating a slow retreat of active, grounded ice from the LGM position on the outer shelf toward Store Hellefiskebanke.

Fig. 1A + B:

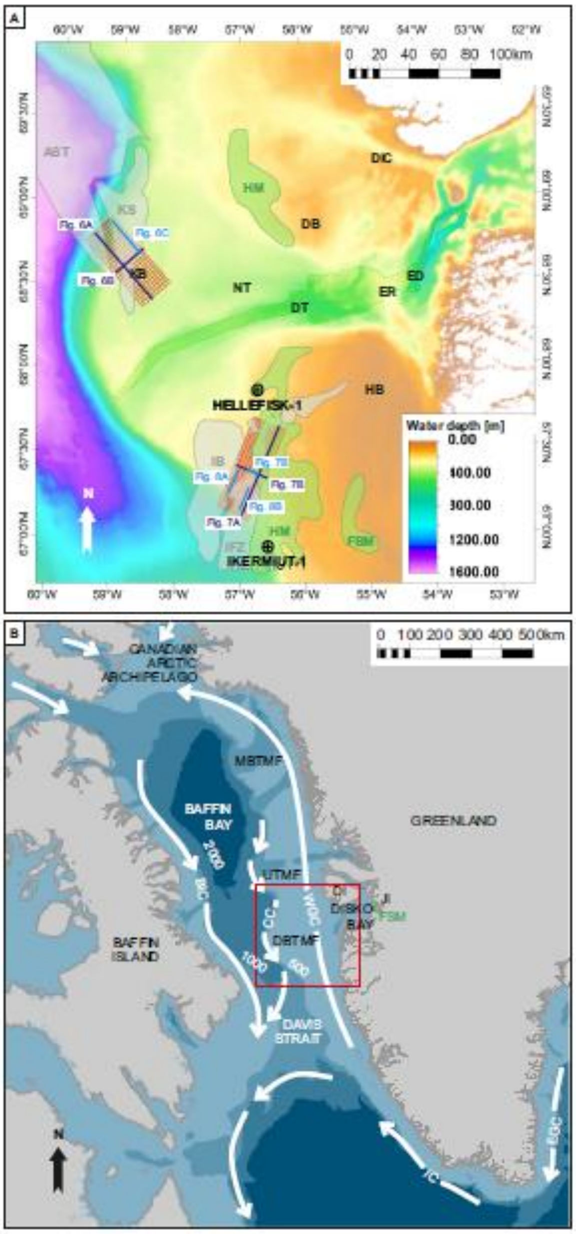

A
Water depth [m]
HELLEFISK-1
IKERMIUT-1
B
CANADIAN ARCTIC ARCHIPELAGO
BAFFIN BAY
GREENLAND
BAFFIN ISLAND
DISKO BAY
DAVIS STRAIT
MBTMF
UTMF
DBTMF

Fig. 2:

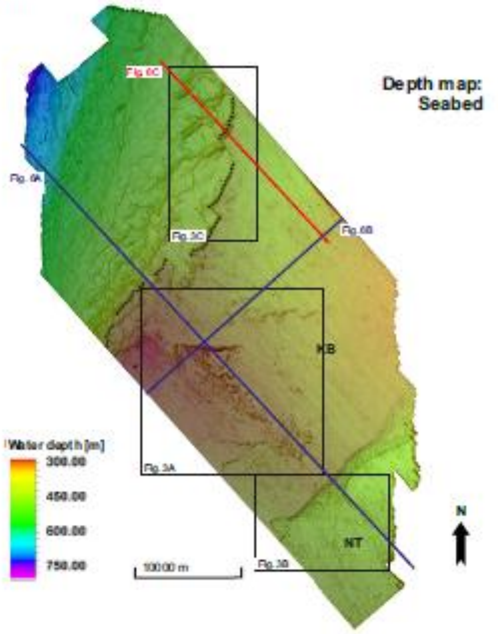

Depth map:
Seabed
Fig. 6C
Fig. 6A
Fig. 6B
Fig. 3C
Fig. 3A
Fig. 3B
KB
NT
Water depth [m]
300.00
450.00
600.00
750.00
10000 m
N

Fig. 3A - C:

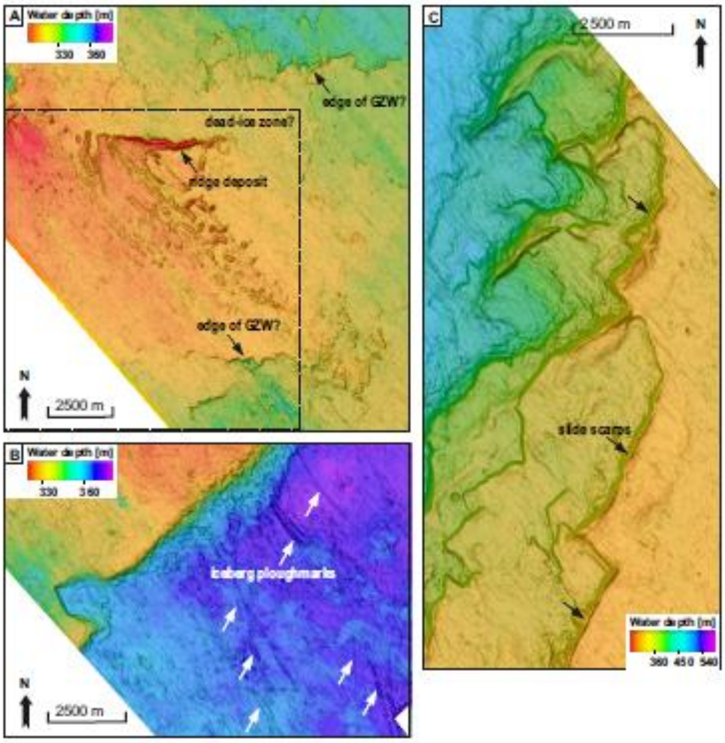

A
Water depth [m]
330
360
edge of GZW?
dead-ice zone?
ridge deposit
edge of GZW?
N
2500 m
B
Water depth [m]
330
360
iceberg ploughmarks
N
2500 m
C
2500 m
N
slide scarps
Water depth [m]
360
450
540

Fig. 4:

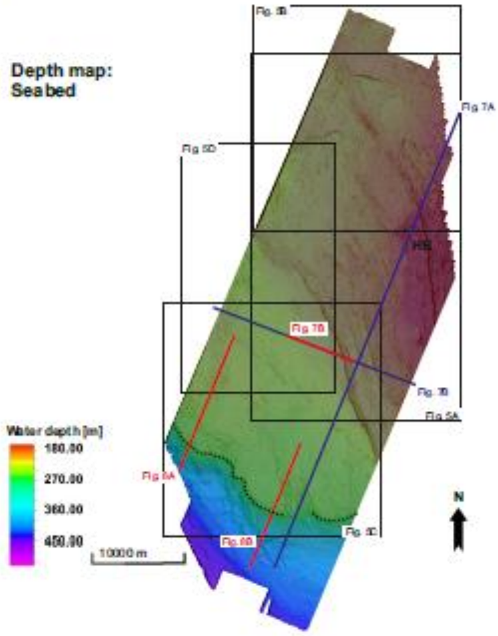

Depth map:
Seabed
Fig 7A
Fig 5D
HS
Fig 7B
Fig 5A
Water depth [m]
180.00
270.00
360.00
450.00
Fig 6A
Fig 6B
Fig 5C
10000 m
N

Fig. 5A - D:

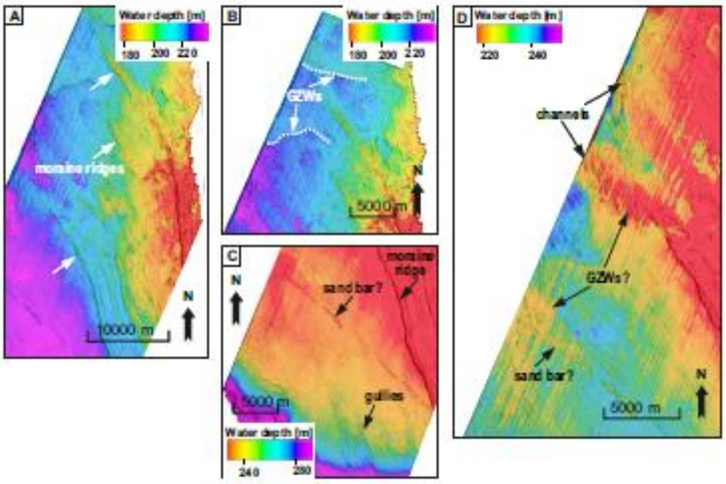

A
Water depth [m]
180
200
220
moraine ridges
10000 m
N
B
Water depth [m]
180
200
220
GZWs
5000 m
N
C
N
moraine ridge
sand bar?
gullies
5000 m
Water depth [m]
240
280
D
Water depth [m]
220
240
channels
GZWs ?
sand bar?
5000 m
N

Fig. 6A - C:

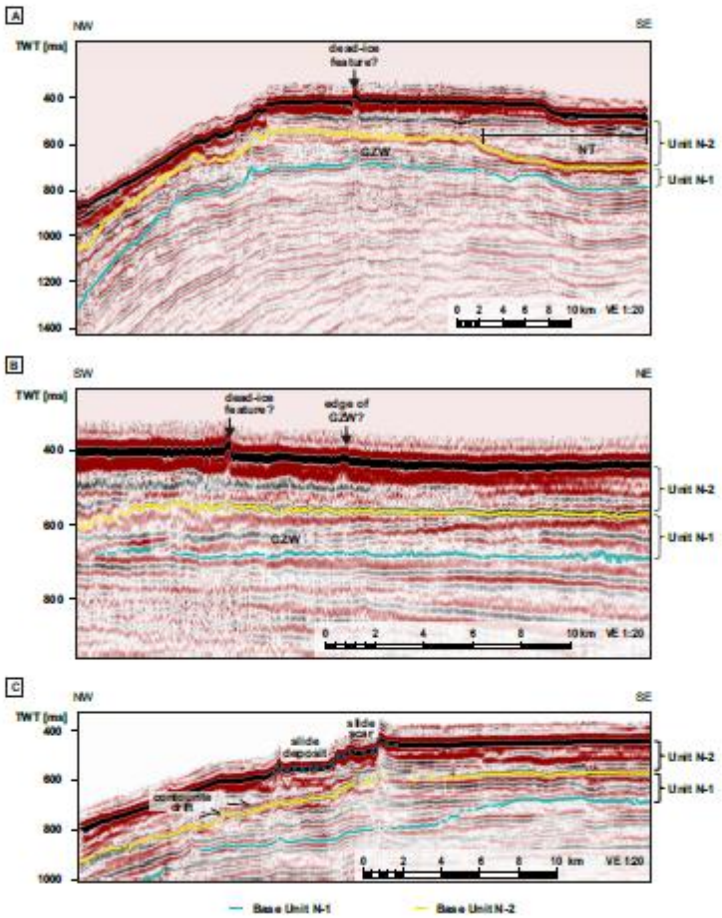

A
NW
SE
TWT (ms)
dead-ice feature?
GZW
NT
Unit N-2
Unit N-1
B
SW
NE
dead-ice feature?
edge of GZW?
C
slide deposit
slide scar
contourite drift
10 km
VE 1:20
Base Unit N-1
Base Unit N-2

Fig. 7A + B:

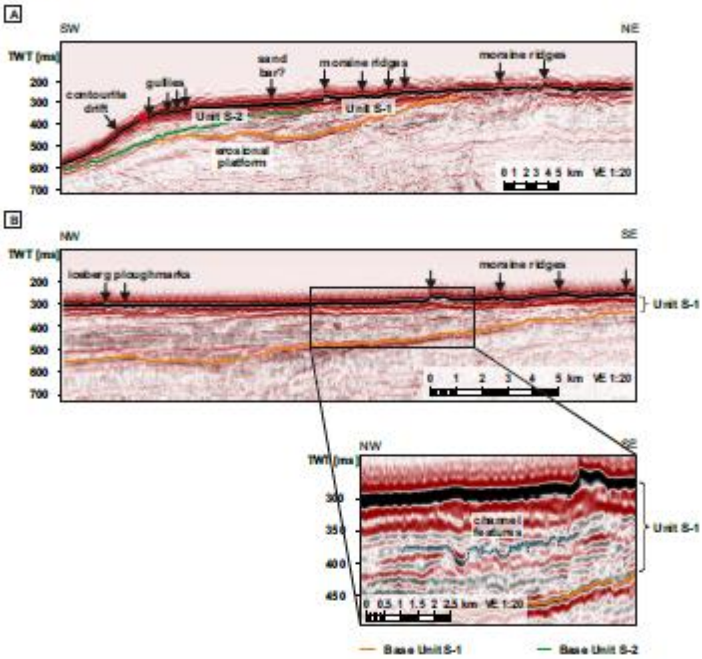

A
SW
NE
TWT (ms)
contourite drift
gullies
sand bar?
moraine ridges
moraine ridges
Unit S-2
Unit S-1
erosional platform
0 1 2 3 4 5 km VE 1:20
B
NW
SE
TWT (ms)
iceberg ploughmarks
moraine ridges
Unit S-1
0 1 2 3 4 5 km VE 1:20
NW
SE
TWT (ms)
channel features
Unit S-1
0 0.5 1 1.5 2 2.5 km VE 1:20
Base Unit S-1
Base Unit S-2

Fig. 8A + B:

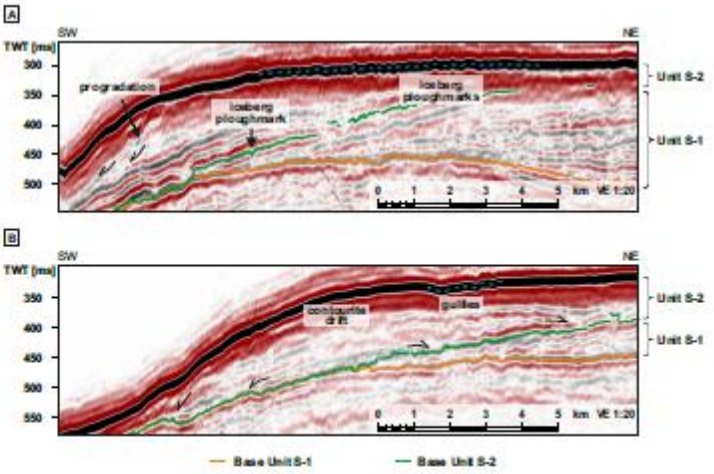
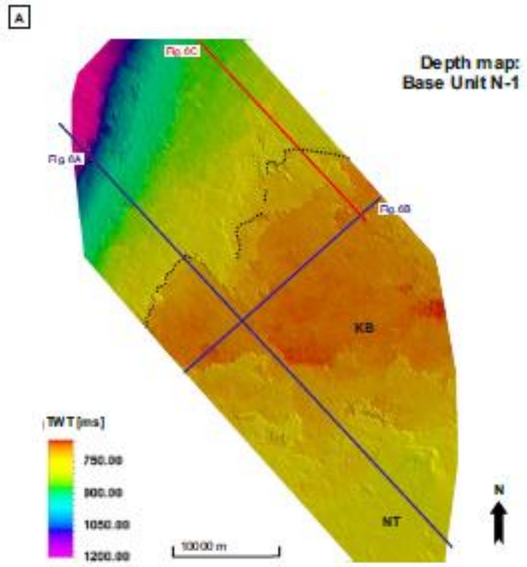

A
SW
NE
TWT [ms]
300
350
400
450
500
progradation
Iceberg ploughmark
Iceberg ploughmarks
Unit S-2
Unit S-1
0 1 2 3 4 5 km VE 1:20
B
SW
NE
TWT [ms]
350
400
450
500
550
contourite drift
gullies
Unit S-2
Unit S-1
0 1 2 3 4 5 km VE 1:20
Base Unit S-1
Base Unit S-2

Fig. 9A + B:


A
Depth map:
Base Unit N-1
Fig 6C
Fig 6A
Fig 6B
KB
NT
TWT [ms]
750.00
900.00
1050.00
1200.00
10000 m
N

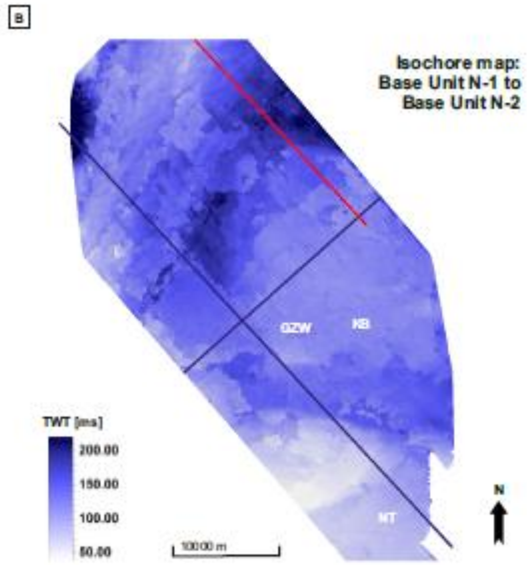
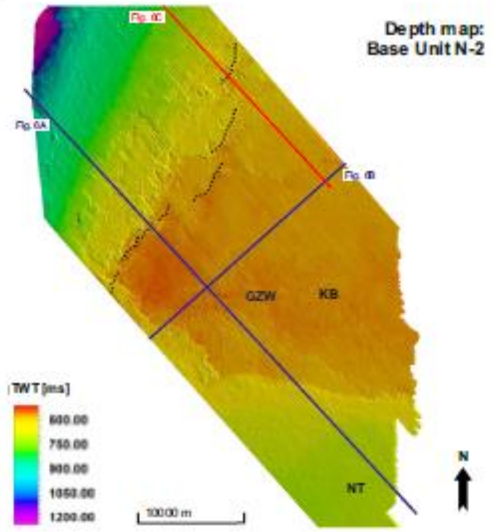

B
Isochore map:
Base Unit N-1 to
Base Unit N-2
GZW
KB
NT
TWT [ms]
200.00
150.00
100.00
50.00
10000 m
N

Fig. 10A + B:

A


Depth map:
Base Unit N-2
GZW
KB
NT
TWT [ms]
600.00
750.00
900.00
1050.00
1200.00
N

B

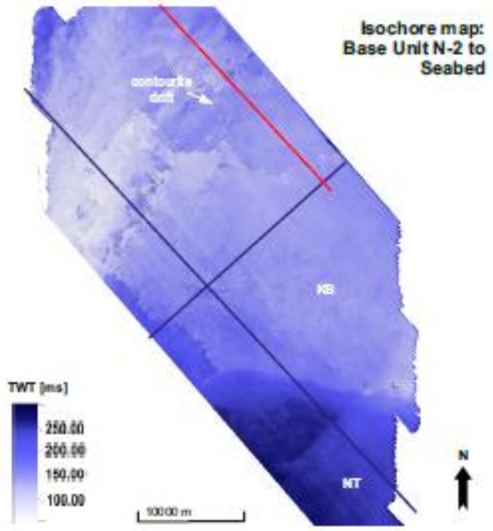
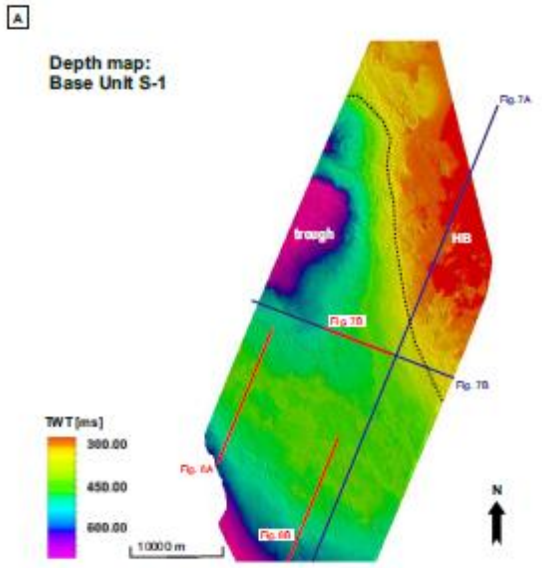

Isochore map:
Base Unit N-2 to
Seabed
KB
NT
TWT [ms]
250.00
200.00
150.00
100.00
N

Fig. 11A + B:


A
Depth map:
Base Unit S-1
trough
HB
Fig.7A
Fig.7B
Fig. 7B
Fig. 6A
Fig. 6B
TWT [ms]
300.00
450.00
600.00
10000 m
N

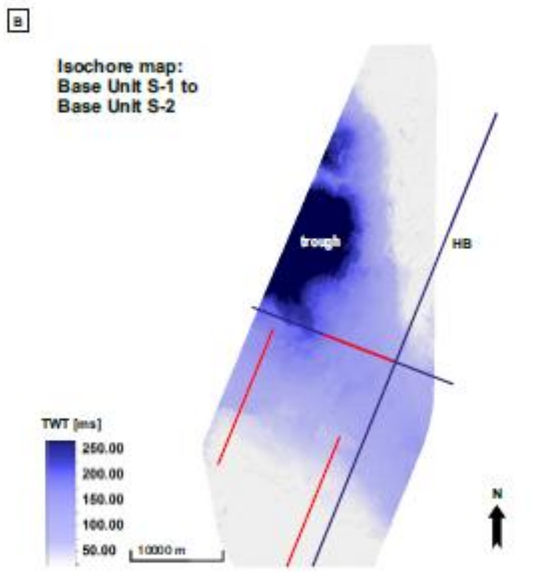

B
Isochore map:
Base Unit S-1 to
Base Unit S-2
trough
HB
TWT [ms]
250.00
200.00
150.00
100.00
50.00
10000 m
N

Fig. 12A + B:

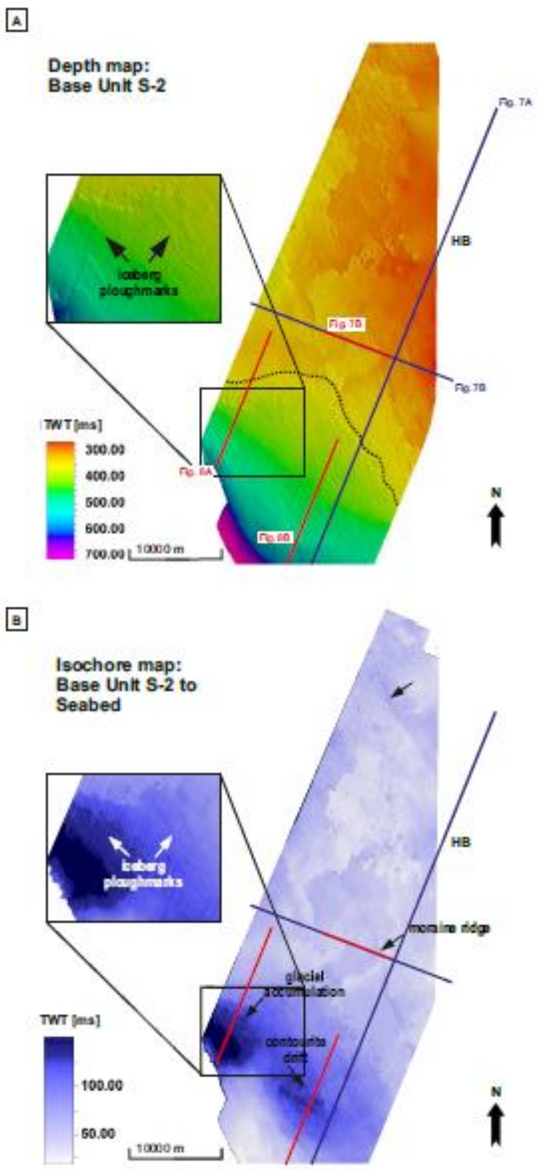
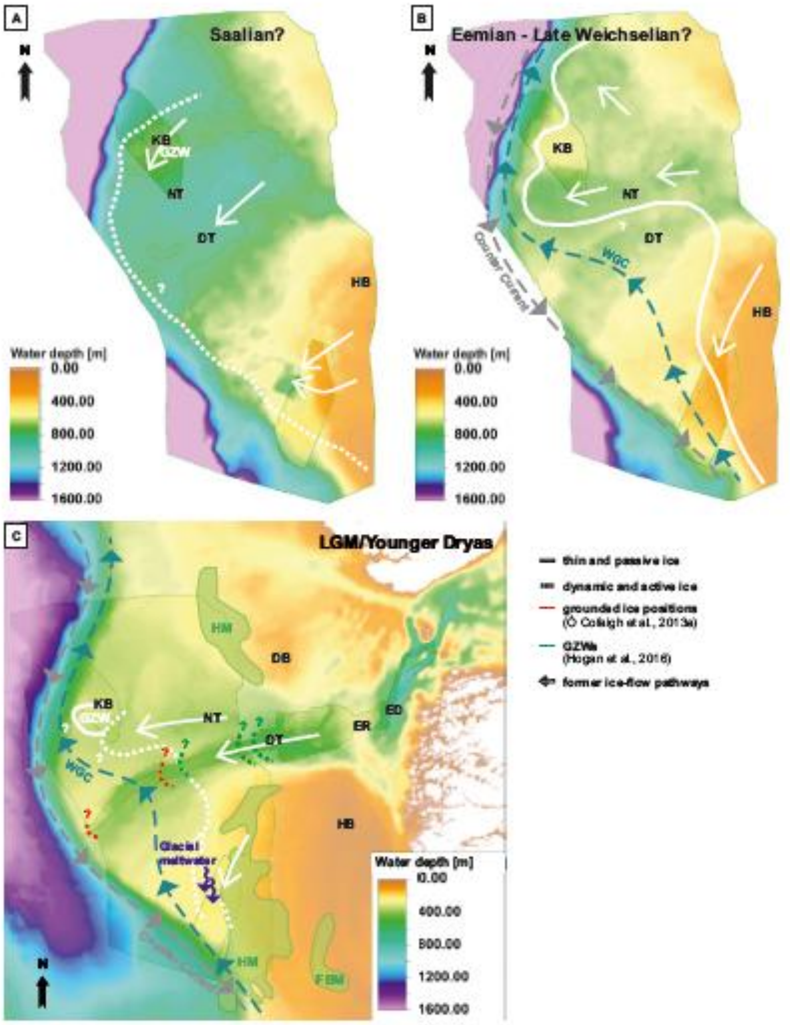

A
Depth map:
Base Unit S-2
Fig. 7A
HB
Iceberg
ploughmarks
Fig. 7B
Fig. 7B
TWT [ms]
300.00
400.00
500.00
600.00
700.00
10000 m
Fig. 8A
Fig. 8B
N
B
Isochore map:
Base Unit S-2 to
Seabed
HB
Iceberg
ploughmarks
moraine ridge
glacial
accumulation
contourite
drift
TWT [ms]
100.00
50.00
10000 m
N

Fig. 13A - C:


A
N
Saalian?
KB
GZW
NT
DT
HB
?
Water depth [m]
0.00
400.00
800.00
1200.00
1600.00
B
N
Eemian - Late Weichselian?
KB
NT
DT
WGC
HB
Counter Current
Water depth [m]
0.00
400.00
800.00
1200.00
1600.00
C
LGM/Younger Dryas
HM
DB
KB
GZW
NT
DT
ER
ED
WGC
HB
Glacial meltwater
HM
FBM
N
Water depth [m]
0.00
400.00
800.00
1200.00
1600.00
thin and passive ice
dynamic and active ice
grounded ice positions
(Ó Cofaigh et al., 2013a)
GZWs
(Hogan et al., 2016)
former ice-flow pathways

Highlights

- A different glacial regime for the two areas hints at the control of local factors.
- The buried section suggests major glacial advances to the shelf margin.
- Subsequently, the outer margin was influenced by glacimarine sedimentation.
- After the LGM, the northern sector indicates grounding of thin and passive ice.
- The seabed in the south indicates a slow and stepwise retreat of grounded ice.